Filtered Simulations of Turbulence in a Reactor Rod Bundle Flow

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Although RANS (Reynolds averaging of the Navier-Stokes equations) turbulence models provide adequately accurate solutions for many engineering problems at a reasonable computational cost, there is no single RANS model of universal applicability. Moreover, in many important applications the RANS model predictions for flow distributions, heat transfer coefficients, and thermal mixing can be significantly off. Examples of such applications are flows in pressurized water reactor rod bundles with mixing vanes and flows in gas cooled reactors where buoyancy effects are significant. Because direct numerical simulation (DNS) of turbulence for large Reynolds numbers and for system-size scales of interest are not still computationally practical, LES (large eddy simulation) and coarse DNS models of turbulence, which are computationally less demanding than DNS, hold the promise to remedy the shortcomings of the RANS models in many important applications. LES is predicated on a scale separation mechanism, usually in the form of a filter, to isolate the resolved (simulated) scales from the subgrid scales (SGS). An essential part of LES is to account for the effects of the missing SGS terms; these typically appear as enhanced diffusion in the Navier-Stokes equations.

Here, we consider simulations in a reactor rod bundle in which the scale separation and dissipation are combined in a single step. Rather than filter the nonlinear terms, as is common in most LES applications, we directly filter the velocity field at the end of each timestep. This approach serves several purposes: it yields a stable and numerically tractable computation at (nominally) large Reynolds numbers; it yields a smooth differentiable function that can be properly advanced by numerical discretization with minimal phase error; and it removes energy from the highest resolvable modes on the grid, thereby avoiding the energy pile-up typical of underresolved turbulence spectra.

Discretization is based on the spectral element method (SEM) coupled with third-order characteristics-based time-stepping, as described in [1]. The SEM employs brick elements with local expansions based on Nth-order orthogonal polynomial expansions. In the present application, the domain is partitioned into 1,040 elements (20 layers comprising 52 elements each; see Fig. 1) of order N = 15. At the end of each timestep, the velocity is filtered by damping the highest modes. Following Boyd [2], if u_{ijk} is the set modal basis coefficients for u in a particular element, then the coefficients for the filtered field $\bar{u}$ are given by $\bar{u}_{ijk} := \sigma_i \sigma_j \sigma_k u_{ijk}$, where the σs are the modal damping coefficients. Here, we take $\sigma_N = 0.9$, $\sigma_{N-1} = 0.95555$, $\sigma_{N-2} = 0.98888$, and $\sigma_k = 1$ for $k < N - 2$. In a well-resolved calculation, the solution will be smooth, and the amount of energy in the high-wavenumber coefficients will be exponentially small. The filter, which operates only on the highest wavenumbers, has the desirable property of not influencing the well-resolved parts of the flow—it affects only the underresolved regions, which is precisely what is needed for turbulence applications.

A series of experiments performed in the late 1970s at Pacific Northwest National Laboratory [3] investigated turbulent flow phenomena in a 7 x 7 rod bundle consisting of rods 0.996 cm in diameter, with a pitch of 1.369 cm. Measurements were made at Reynolds numbers of 1.4 x 10^4, 2.9 x 10^4, and 5.8 x 10^4. The important features of the flow were not significantly dependent on the Reynolds number. In this work the experiment with a Re number of 2.9 x 10^4 (inlet velocity of 1.74 m/s) was used as benchmark.

Because the computational demands of coarse DNS are high, a small section of the bundle, as shown in Fig. 1, was simulated. This section has a length of 8.89 cm in the main flow direction; its left boundary is 1.05 cm away from the bundle wall and is far enough from spacer grids to ensure that the grids have no effect on the turbulence of the flow in this section. Code predictions were compared with measurements of the turbulence intensity (local fluctuating axial velocity over local axial velocity) and the normalized axial (flow direction) mean velocity (local mean velocity/velocity at the bundle inlet) at points on a line perpendicular to the bundle wall (symmetry axis of Fig. 1) and on a plane perpendicular to the direction of the main flow. The measurement error for the velocity is ±11% and for the turbulence intensity ±16%. The maximum discrepancy between velocity predictions and measurements is 1.7% (Fig. 2a), while the predicted turbulence intensity is within the experimental error band.

Figure 2b shows the distribution of the normalized velocity u^+ as a function of the normalized distance y^+ from the rod surface along the 45° channel diagonal. The normalized velocity and distance are defined by

$$u^+ = u/u_\tau$$

$$y^+ = yu_\tau/v$$

$$u_\tau = \mu \, du/dy,$$

where u is the time-averaged velocity in the flow direction, v and μ are the kinematic and dynamic viscosity, respectively, and y is the distance normal to the rod surface. Figure 2 also shows that the normalized velocity fits the logarithmic law

$$u^+ = B + \frac{1}{k} \ln y^+$$

with k = 0.41 and **B** = 5.0. Although the benchmark experiment did not provide velocity distributions along the diagonal to validate the predicted logarithmic law of the wall, this prediction is very close to the logarithmic fit

$$u^+ = B + \frac{1}{k} \ln y^+$$

with k = 0.418 and B = 5.45 for p/d (pitch to diameter) = 1.107, and k = 0.4 and B= 5.5 for p/d = 1.194, fitting the experimental data of References 4 and 5, respectively.

In conclusion, the filtered spectral element approach provides a faithful simulation of the benchmark flow in a rod bundle.

References

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Acknowledgements

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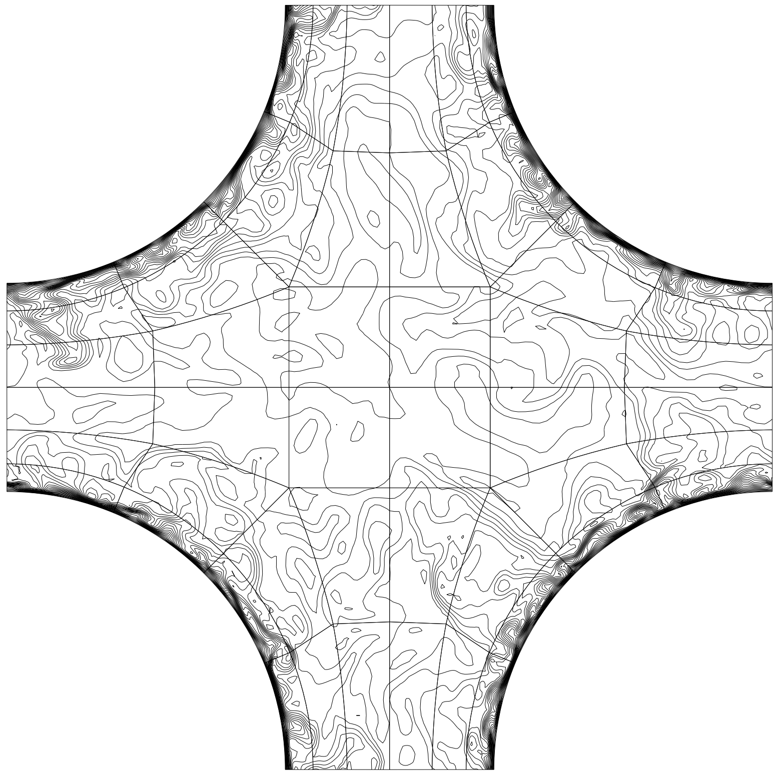
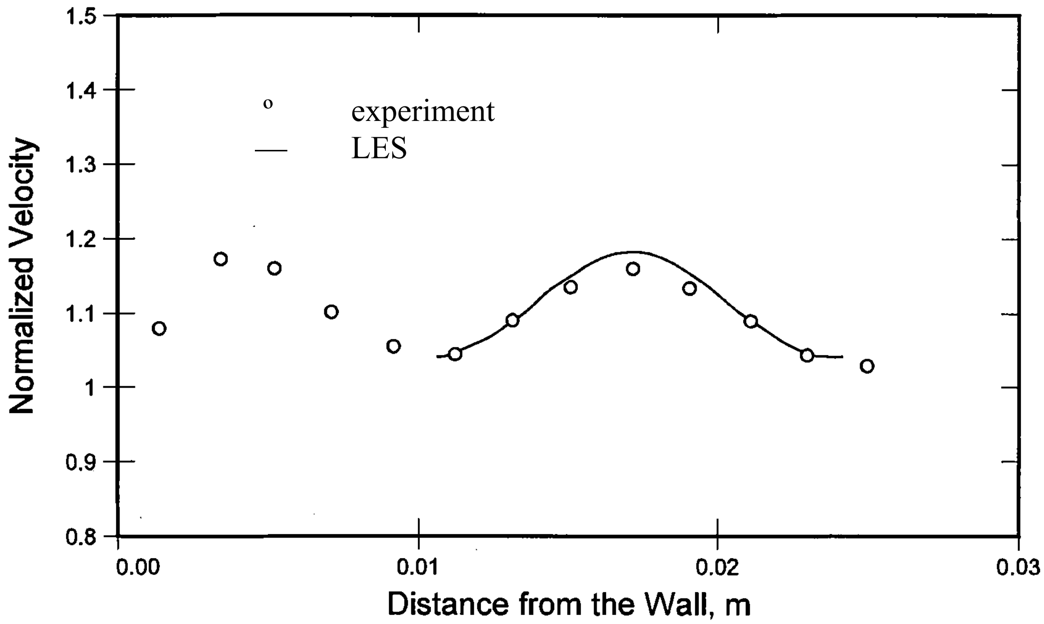
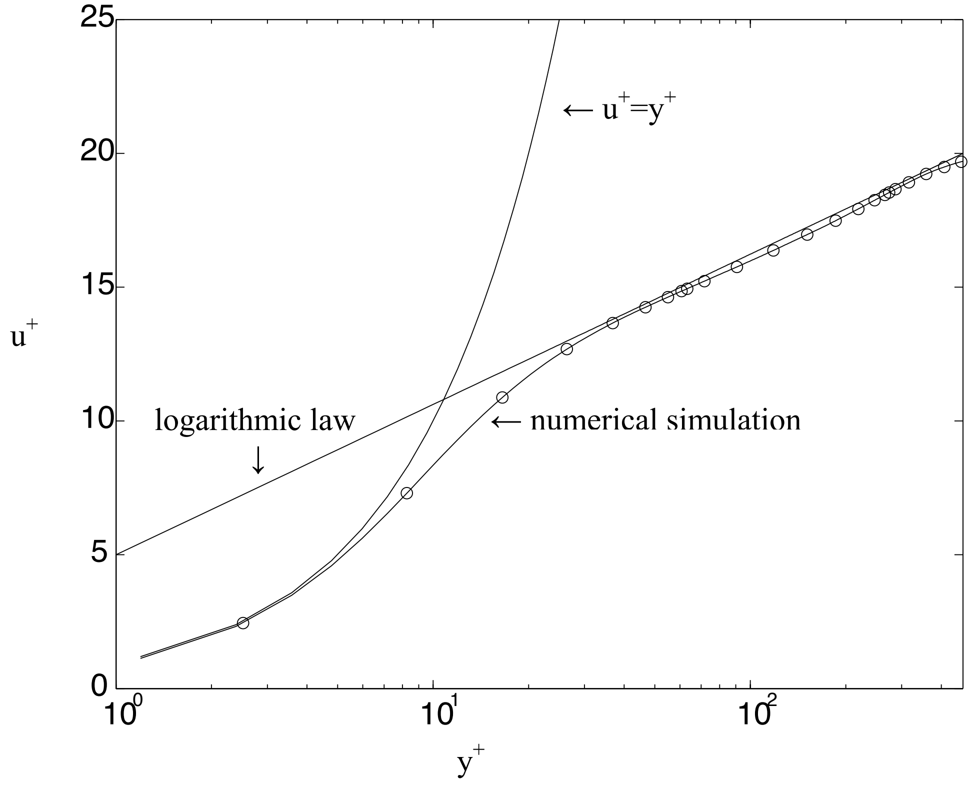


Figure 1. Element structure and contours of velocity component in flow direction.



2a: Velocity versus distance from bundle wall.



2b: u^+ versus y^+

Figure 2. Velocity distributions.

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